Naval Submarine Medical Research Laboratory

NSMRL Report No. 1240 **06 JULY 2005**

Advanced Binaural Sonar Display Using Spatial Vernier Beamforming.

by
Joseph S. Russotti
Mark A. Creese
and
Thomas P. Santoro

Approved and released by

C.J. Daniel, Captain MC , USN
Commanding Officer
Naval Submarine Medical Research Laboratory

Approved for public release; distribution unlimited

Advanced Binaural Sonar Audio Display using Spatial Vernier Beamforming

by
Joseph S. Russotti
Mark A. Creese
and
Thomas P. Santoro

NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

REPORT No. 1240

Approved and released by

J.C. Daniel, CAPT MC, USN
Commanding Officer
Naval Submarine Medical Research Laboratory

SUMMARY PAGE

Problem

Operating in a dangerously sensor-limited closed environment, submarine sonar operators using current systems are plagued by primitive sensory interfaces inherited from earlier hardware designs. The inappropriate match to the operator's perceptual capability results in inefficient, often ineffective operator performance. These inefficiencies are exacerbated as submarines increasingly operate in the littoral where, at now reduced ranges from quieter threat targets, detection requires immediate action for crew safety.

Findings

Present use of the sonar operator's auditory ability ignores the superior acuity of the mammalian binaural system. In humans, this system is sensitive to minute instantaneous differences in phase, intensity and time of arrival between its' two channels. The present research developed, and perceptually tested, a binaural auditory display that optimized the noise correlation between a pair of formed listening beams. To generate the necessary perceptual characteristics essential for the binaural display, a breakthrough audio beam-forming process was developed that formed beams from a simple linear hydrophone array which were *focused* at two different distances but in the same direction. This unique processing named Spatial Vernier Beamforming (SVBF) maintained the *essential* high noise correlation between the pair of formed directional beams. Once appropriate beamforming was proven feasible, laboratory testing was undertaken to quantify perceptual performance. A representative sample of 14 sonar contacts were beamform processed, stored as wavefiles and systematically presented to a group of 17 highly experienced sonar operators. Results show a highly significant 6.8 dB detection improvement over the current single beam display. This improvement represents the ability to acoustically detect targets at more than <u>twice</u> the distance currently achieved.

Application

The signal processing technology developed here will provide an advanced auditory display which allows immediate interaural comparisons of pairs of focused beams. This broader coverage binaural real-time display is particularly well suited in littoral warfare. Performance gains such as: 1) simultaneous vs. serial comparison of beams of different distance, for more rapid detection of acoustic changes (including transients), 2) increased real-time information on target distance, 3) reduced operator uncertainty and increased alerting cues from target motion 'across the head' during sequential ranging, will significantly enhance crew safety in modern close-in operations. It can be linked to photonics mast display.

The SVBF dual beam data is ideal for adaptive *real-time* signal processing, since the noise common to the two beams (which is highly correlated by beamform-design) can be mathematically removed to expose the target. As a result SVBF processes are amenable to real-time digital signal extraction for 3-D audio displays which are ideal for situational awareness.

Based upon our positive findings using the simpler linear sonar array, SVBF processing is currently undergoing theoretical application to the Wide Aperture Array (WAA) which has far better bearing resolution. The broader bandwidth more perceptually useful WAA will provide a greater challenge to applying this spatial-vernier beam-forming technique to a more complex beam-formed array.

OPERATIONAL ABSTRACT

Operating in a dangerously sensor-limited closed environment, submarine sonar operators using current systems are plagued by primitive sensory interfaces inherited from earlier hardware designs. The inefficient match to the operator's perceptual capability is exacerbated as submarines increasingly operate in the littoral where, at now reduced ranges from quieter threat targets, detection requires immediate action for crew safety.

Present use of the sonar operator's *auditory* ability ignores the superior acuity of the mammalian binaural system. In humans, this system is sensitive to minute instantaneous differences in phase, intensity and time of arrival between its' two channels. This research developed, and perceptually tested, a binaural auditory display that optimized the noise correlation between a pair of formed listening beams. To generate the necessary perceptual characteristics essential for the binaural display, a breakthrough audio beam-forming process was developed that formed beams from a simple linear hydrophone array which were *focused* at two different distances but in the same direction. This unique processing named Spatial Vernier Beamforming (SVBF) maintained the *essential* high noise correlation between the pair of formed directional beams. Once appropriate beamforming was proven feasible, laboratory testing was undertaken to quantify perceptual performance. A representative sample of 14 sonar contacts were beamform processed, stored as wavefiles and systematically presented to a group of 17 highly experienced sonar operators. Results show a highly significant 6.8 dB detection improvement over the current single beam display. This improvement represents the ability to acoustically detect targets at more than <u>twice</u> the distance currently achieved.

The signal processing technology developed here will provide an advanced auditory display which allows immediate interaural comparisons of pairs of focused beams. This broader coverage binaural real-time display is particularly well suited in littoral warfare. Performance gains such as: 1) simultaneous vs. serial comparison of beams of different distance, for more rapid detection of acoustic changes (including transients), 2) increased real-time information on target distance, 3) reduced operator uncertainty and increased alerting cues from target motion 'across the head' during sequential ranging, will significantly enhance crew safety in modern close-in operations. It can be linked to photonics mast display.

The SVBF dual beam data is ideal for adaptive *real-time* signal processing, since the noise common to the two beams can be mathematically removed to expose the target. As a result SVBF processes are amenable to real-time digital signal extraction for presentation in 3-D audio displays which are ideal for situational awareness.

Based upon our positive findings using the simpler linear sonar array, SVBF processing is currently undergoing theoretical application to the Wide Aperture Array (WAA) which has far better bearing resolution. The broader bandwidth more perceptually useful WAA creates a greater challenge to applying this spatial-vernier beam-forming technique to a more complex beam-formed array.

ABSTRACT

Operating in a dangerously sensor-limited closed environment, submarine sonar operators are plagued by primitive sensory interfaces inherited from earlier hardware designs. The inefficient match to the operator's perceptual capability is exacerbated as submarines increasingly operate in the littoral where, at now reduced ranges from quieter threat targets, detection requires immediate action for crew safety.

Present use of the sonar operator's *auditory* ability ignores the superior acuity of the mammalian binaural system. In humans, this system is sensitive to minute instantaneous differences in phase, intensity and time of arrival between its' two channels. This research developed, and perceptually tested, a *binaural* auditory display that optimized the essential noise correlation between a pair of formed listening beams. To generate the necessary perceptual characteristics for the binaural display, a breakthrough audio beam-forming process formed beams from a simple linear hydrophone array which were *focused* at two different distances but in the same direction. This unique processing named Spatial Vernier Beamforming (SVBF) maintained the essential high noise correlation between the pair of formed directional beams. Once appropriate beamforming was proven feasible, laboratory testing was undertaken to quantify perceptual performance. A representative sample of 14 sonar contacts were beamform processed, stored as wavefiles and systematically presented to a group of 17 highly experienced sonar operators. Results show a highly significant 6.8 dB detection improvement over the current single beam display. This improvement represents the ability to acoustically detect targets at more than <u>twice</u> the distance currently achieved.

This signal processing technology provides an advanced auditory display which allows immediate interaural comparisons of pairs of focused beams. This broader coverage *binaural* real-time display is particularly well suited in littoral warfare. Performance gains such as: 1) simultaneous vs. serial comparison of beams of different distance, for more rapid detection of acoustic changes (including transients), 2) increased *real-time* information on target distance, 3) reduced operator uncertainty and increased alerting cues from target motion 'across the head' during sequential ranging, will significantly enhance crew safety in modern close-in operations. It can be linked to photonics mast display.

The SVBF dual beam data is ideal for adaptive *real-time* signal processing, since the noise common to the two beams can be mathematically removed to expose the target. As a result SVBF processes are amenable to real-time digital signal extraction for presentation in 3-D audio displays which are ideal for situational awareness.

Following positive findings using the simpler linear sonar array, SVBF processing is currently undergoing theoretical application to the Wide Aperture Array (WAA) which has far better bearing resolution. The broader bandwidth more perceptually useful WAA creates a greater challenge to applying this spatial-vernier beam-forming technique to a more complex beam-formed array.

ADMINISTRATIVE INFORMATION

This investigation was conducted under work unit #61153N-M04508.518-50211, entitled "Advanced Binaural Displays for Collision Avoidance in Close-in Undersea Environments." The views expressed in this report are those of the author(s) and do not reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government. This report was approved for publication on 06 July 2005, and designated as Naval Submarine Medical Research Laboratory Report #1240.

INTRODUCTION

The primary objective in this research is to apply the most sensitive capabilities of human auditory perception to sonar systems. Our present use of the sonar operator's auditory ability ignores the superior acuity of the mammalian binaural system. Heightened in lower species through moveable and enlarged external ears (pinna), this system, effectively used for determining spatial location of a predator, is sensitive to minute differences in phase, intensity and time of arrival between its two channels. We will use this heightened interaural sensitivity to enhance detection of relative differences between two simultaneously received external channels.

Because of the reductions in steady-state tonal information from targets, signal-averaging (time-integrating) target-detection systems are losing their long-range detection advantage. Operating in a dangerously sensor-limited closed environment, submarine-sonar operators using current systems are plagued by primitive sensory interfaces inherited from earlier hardware designs. The inappropriate match to the operator's perceptual capability results in inefficient, often ineffective, operator performance. These inefficiencies are exacerbated as submarines increasingly operate in the littoral where, at now reduced ranges from quieter threat targets, detection requires immediate action for crew safety. Normally, as a function of propagation losses through water, higher frequencies radiated from the target are reduced. Now, as a consequence of closer ranges the upper-bandwidth of the available signal has increased. These extended bandwidth conditions are appropriate for auditory perception if the signal is presented in a perceptually optimal manner. It is commonly accepted that rapid detection and classification of acoustic transients is best performed by listening to the acoustic environment. However, on current passive sonar systems the operator listens to the output of a single high-gain formed beam that can be "trained" in azimuth. All comparisons of the acoustic signal occurring at various bearings relative to own ship are made serially.

In the everyday world, both the detection and localization of sounds in auditory space that is cluttered with ambient interfering stimuli or "noise" depends on the binaural system. The two ears sample the sound field on either side of the head and, as a result of their positions and external geometry, receive different information. Time differences at low frequencies, amplitude differences at higher frequencies and sound reflection differences into the ear canal caused by the unique shape of the outer ear are all available for inter-aural comparison. Directional information, distance information, elevation of sound sources and other spatial cues are constantly binaurally processed for affirmation against other sensory cues. Without such information, performance is severely degraded using only one of the two ears. Numerous investigations noted by Jeffress (1972), by Durlach (1972), Durlach and Colburn (1978) and Blauert (1983) have documented and attempted to quantify these binaural phenomena. Any improvement in detection that results from using two ears instead of one is called masking level difference (MLD). Since the early work by Hirsch (1948) to quantify the detection advantage afforded by binaural presentation using tones in noise, and by Licklider (1948) using speech signals, literally hundreds of laboratory studies have refined knowledge of binaural sensory processes. All of this binaural sensory processing relies upon the consistency and predictability of the environment in terms of physical acoustics. It is therefore essential that any novel binaural presentation of information maintain the essential characteristics of the real world environment.

In passive sonar systems an array of listening hydrophones is used to gather the acoustic signal (see Figure 1). So-called *beamforming* is used to time-align the signal arriving at the individual hydrophones in the array from a particular direction. For a *particular* direction, the signals from farthest hydrophones are processed with least delay, while those closest to the selected direction are delayed the most. Compensating for time-of-arrival differences, due to the relative location of each hydrophone in the configured array, allows the signal emanating from a particular direction to be summed. In that time-alignment process, the natural correlation that existed in the noise surrounding adjacent hydrophones is destroyed for a reason. Since the sea-noise in the time shifted signal from each hydrophone is de-correlated, it does not sum. But, the signal from the selected direction does. Most relevant, is the fact that under those currently existing beamforming constraints, forming a similar directional beam a few degrees different in *azimuth* will generate a composite background noise substantially *different* from that generated in the adjacent formed beam (Deeb, 2004). That is drastically different to the interaural noise heard in a real-world sound field.

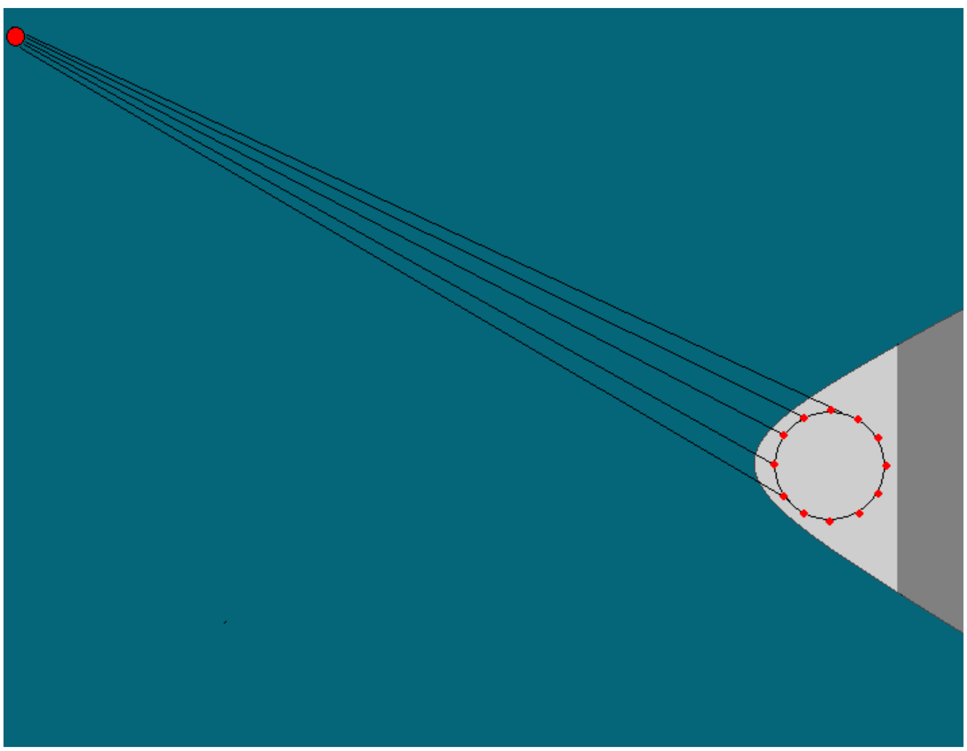

Figure 1. Conventional beamforming

Using *novel* simultaneous beamforming, we must develop the basis for a dual-beam display, which allows interaural comparisons for rapid detection of differences. Pivotal to the actual implementation of such a display in a practical application, is the ability to generate the essential degree of noise correlation and target-intensity difference to the two display channels. The channels must replicate the correlation which occurs between the two ears in a real-world acoustic sound field. Further, the pair must be able to sequentially and smoothly traverse in azimuth across the sound field.

The critical aspects here are the ability to recreate the high degree of noise cross-correlation between beams, that physically exists when two directional beams overlap nearly entirely. To the extent that they are projected to slightly different locations, minor instantaneous differences occurring in the two channels should become salient if the background noise in each beam cross-correlates to a high degree. Implicitly, the fidelity of the processed signal must be preserved.

In the recent past, the auditory signal received at the sonar operator's ear had been progressively degraded in sound quality due to its role having been supplanted by signal-averaging processes (Gersch, et al, 1979; Russotti, 1987a, 1987b; Russotti & Marshall, 1987; Hanna et al, 1988; Marshall & Nash, 1990). Evolving signal-processing techniques had been optimized to enhance sonar-operator performance for visually presented information. However, those processing techniques can degrade the auditory signal (Russotti et al, 1993). As applied in older sonar system design, the poor quality of digitally processed audio stems from the fact that digitization parameters were selected for their influence on visual displays. Fortunately, newer Virginia Class 3CI (Command, Control, Communication, and Intelligence) consoles and A-RCI (Advanced Rapid COTS Insertion) sonar consoles have successfully addressed many of these fidelity issues through dual channel audio-quality D/A (digital/analog) converters (Heller et al, 2000, Russotti and Schwaller, 2001).

Given the dual-channel high-resolution auditory interface available on these upgraded systems, perceptually relevant beamforming modifications are possible. Appropriate digital processing provides the opportunity to employ sophisticated dual-beam signal presentation techniques to enhance auditory sonar performance by using innate binaural sensitivity. Data show a significant improvement in detection of sonar targets using an extended-frequency binaural laboratory display which synthetically provides target and noise in one ear and highly correlated noise to the other ear (Russotti & Wojtowicz, 1989). These data also delineate the decrement in performance as a function of reduced noise correlation between the two ears and specify the minimum degree of correlation required for the display.

The demonstration of this binaural advantage or MLD for tones in noise was documented by Hirsch (1948), using pure-tone detection-threshold measurement. Similar laboratory manipulations using actual sonar targets in sea-noise were conducted by Kerivan (1980), who showed a 5 to 7 dB improvement under one of the conditions reported by Hirsch. In that experiment the binaural difference was created by reversing the phase of the target in the two ears, while retaining the identical phase of the noise at both ears. Russotti & Wojtowicz (1989) applied a more practical *experimental* binaural presentation, using target and noise in one ear and highly correlated noise in the other ear. Binaural detection improvement to actual sonar targets in sea-noise was measured as a function of varying degrees of interaural noise correlation. Figure 2 presents a portion of the detection performance data from that research, which shows a significant improvement in detectability, of a sample of 16 targets, as a function of presenting different information

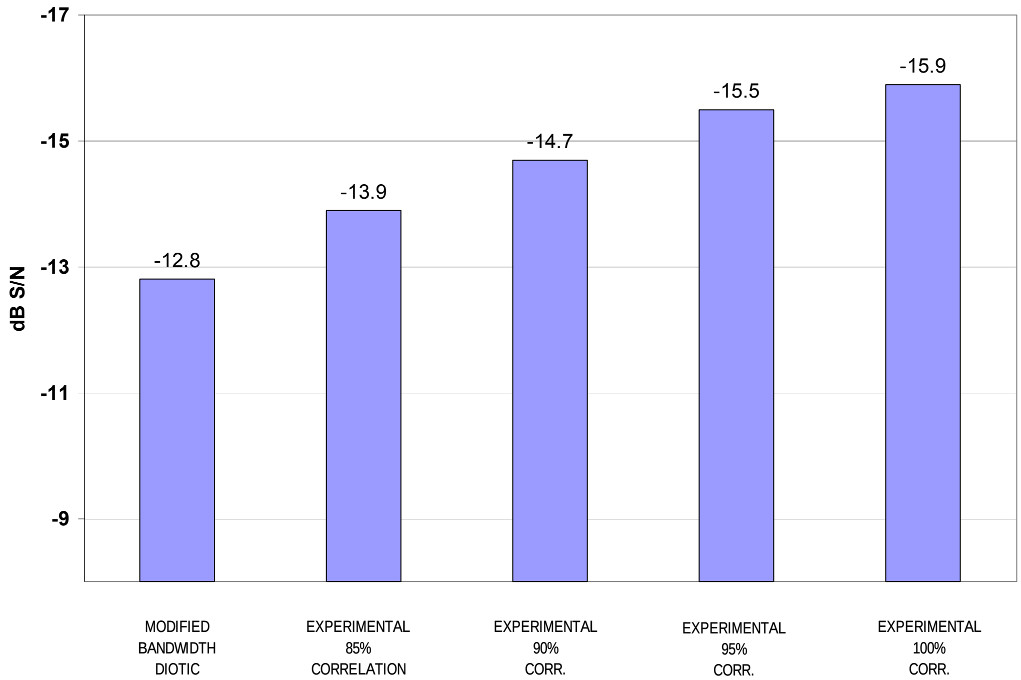

Figure 2. Effects of interaural noise correlation on binaural target detection.

to the two ears (dichotic), over same information to both ears (diotic), while keeping bandwidth exactly the same. Further, improvement increased as the degree of interaural noise correlation, in the experimental condition, increased. There was a significant increase in target detectability as the interaural noise correlation increased from 85% to 100%. Though the method of binaural presentation was different, interaural noise correlation effects were in agreement with the work of Robinson and Jeffress (1963) who, like many others, artificially reversed the interaural phase of the target while keeping the noise to each ear in phase. Such detection improvement is *operationally* highly advantageous, since 6 dB threshold gain doubles the distance or *range* for initial detection.

In the practical application of binaural perceptual improvement to auditory sonar systems, a *steerable* binaural spatial-display was devised, and *demonstrated* in laboratory simulations, which applied simultaneous "beamforming" to generate different information to each ear. These differences are achieved by presenting beams of slightly offset bearing to each ear, so that simultaneous comparisons between adjacent formed beams could be made inter-aurally. As the beams are trained across azimuth any detectable target is first heard in one ear and then, as the second formed beam passes over it, in the other ear. For near-threshold targets, the simultaneous information in the other ear is noise alone. Using this dual-beam method of binaural presentation approaches the experimental condition of target and noise in one ear and noise alone in the other. Importantly, it creates a dynamic interaural change at the two ears, as would a moving sound source in the environment. This display is in contrast to current displays where with a single beam the operator makes serial-listening comparisons as he traverses beams. In effect, the proposed display exploits the human auditory system's binaural ability to spatially detect a difference in sound between two channels, to create the conditions for binaural improvement. In addition, the alerting aspects afforded by the apparent motion of the detectable sound of the target as it is perceived to travel across the head may reduce the operator's criterion for initially recognizing and reporting the presence of a contact. As a further advantage the pair of formed beams, if separated to a greater degree, can double the spatial monitoring available to the operator for close in monitoring of super-threshold events, such as transients.

PROCEDURE

Beamforming Assessment

Beamforming feasibility studies were conducted at Naval Undersea Warfare Center (NUWC), Newport to determine the possibility of generating appropriate beamformed data using novel processing algorithms and hydrophone arrays. The goals were: a) To have the highest cross-correlation at different separations in formed beams; b) To provide the greatest difference in target intensity between the two focused beams. The ideal presentation maintains the highest possible noise-cross-correlation at a useful beam separation. The greater the degree of angular or distance separation, the more likely the two formed beams will provide the greatest relative difference in target intensity to create target and noise in one ear and (effectively) noise alone in the other. The product of this research phase provided theoretical evaluations of dual-beam characteristics. NUWC collaborators were tasked to provide theoretical data on the noise cross-correlation and target level difference between adjacent beams (in bearing) independently formed from the same hydrophone elements of a single array as a function of beam separation. From this analytical research, alternate beamforming algorithms evolved that are intended to maximize the degree of dual-beam cross-correlation over initial algorithms.

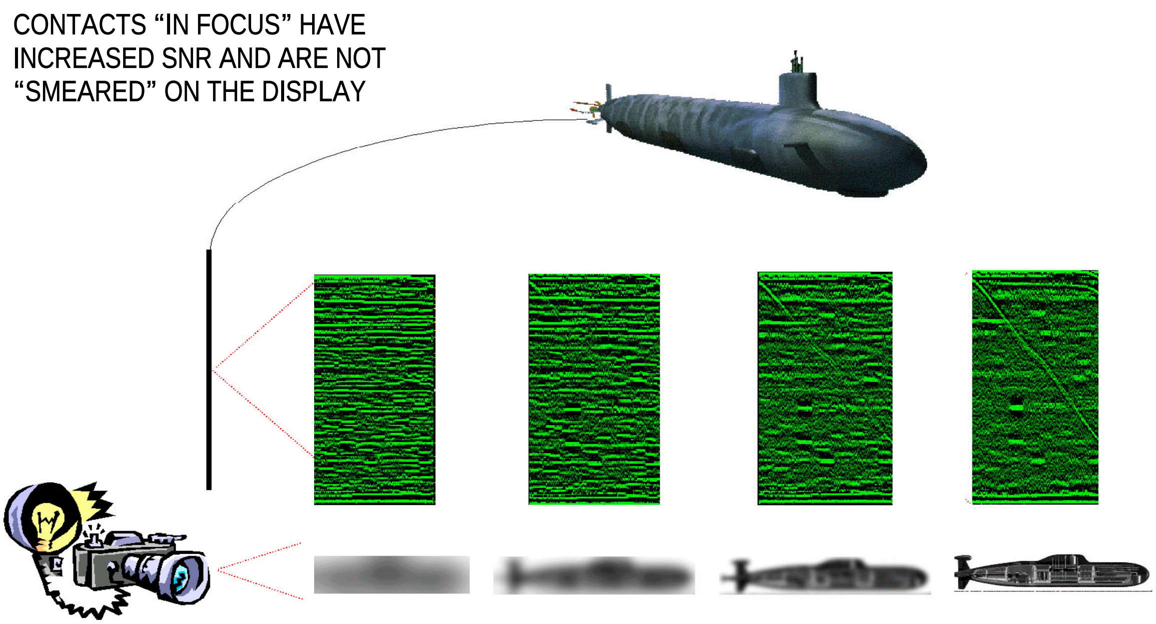

Figure 3. SVBF focuses formed beams to different distances at the same bearing

Assessment, using conventional arrays of various configurations, showed that conventional beamforming obliterated the natural noise correlation that should exist between adjacent areas. Our requirements drove the design of new processing for binaural presentation called Spatial Vernier Beamforming (SVBF) which was applied to the simplest of arrays, the line array.

As seen in Figure 3, by focusing to different distances, SVBF signals are analogous to those created when focusing a camera to different distances. In the camera optics, the target image is blurred at all focal distances other than the actual distance to the object. Similarly SVBF uses pairs of preformed focused beams in a single direction and generates a high signal level when the target is at the focal length of the beam. Similar to the photo-images, the target trace seen in the extreme right panel becomes less visible in each succeeding panel to the left. Because the beams are focused in the same direction, the essential high cross-correlation of ocean noise is maintained with the target level greater in one ear. This target level difference is graphically presented in Figure 4.

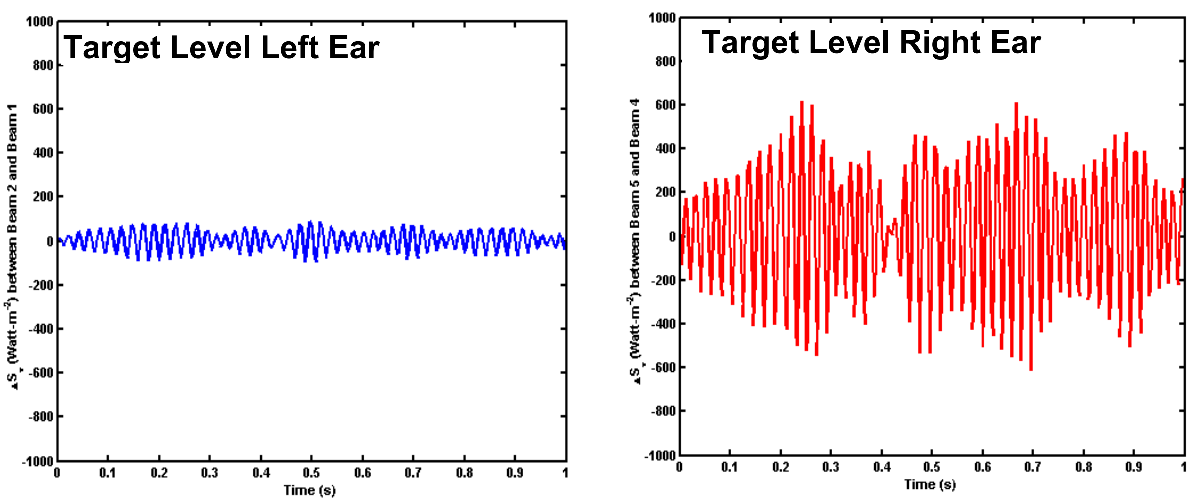

Figure 4. SVBF beam-pair output when one beam is out-of-focus

Perceptual Testing

Presentation procedures used for detection threshold data gathering were identical to those successfully used in Russotti et al. (1993), and earlier in Russotti and Wojtowicz (1989). High quality at-sea target signals, taken from DAT format or 1/4" 1/2 track analog recordings were used as stimuli. The stimuli are an aurally representative sample of 14 relevant sonar contacts chosen from a library of such contacts used extensively in our performance research on experimental sonar displays. Digital wave files of both the targets and a sea-state 2 noise were processed through the SVBF beamforming algorithm for *binaural* (dichotic) presentation as dual beam, or diotic (same signal to both ears) single beam. All other parameters (e.g. bandwidth, distortion, headset fidelity, overall presentation level, etc) were held constant in a repeated measures experimental design. In the dual-beam presentation the target level in the louder *in-focus* beam was the relevant level used for comparison against the single beam.

Subjects
Seventeen highly experienced submarine sonar operator supervisors were used as listeners. All had normal hearing in both ears as measured by routine audiometry.

Experimental Design
A two-way repeated measures design was used to present the normal and experimental binaural listening conditions. Target order and presentation condition were randomized.

Stimulus Characteristics
Dual channel signal-processed wave files of each of the 14 targets were stored in a matrix for presentation according to rule. For each of the 2 presentation conditions, the matrix for each target, consisted of a "stereo" pair of processed wave files in which the *beamformed* target was systematically embedded in sea-state-2 noise over a range of signal-to-noise ratios (S/Ns). The S/Ns ranged from 0 dB (target and noise equal in level), to –40 dB (target 40 dB below the noise). In the SVBF matrices, the left and right channels contained the appropriate differences, in the conventional matrices the information in the "stereo" pair was identical. Conventional and SVBF beamforming was modeled from a linear array.

Test Procedure
Subjects were seated in a sound-booth, and listened over a pair of Sennheiser HD 250 closed circumaural (around the ear) headphones. Responses were collected using a handheld pushbutton switch. Target detection threshold was estimated by rule using an adaptive tracking technique that was developed from the modified International Standards Organization threshold-tracking procedures described by Harris (1980).

The adaptive tracking technique used in threshold estimation required the subject to respond by pressing and releasing a button within specified time limits to indicate target onset and termination within a sea-noise background. The onset of the sea-noise background indicated the start of each listening-trial. Target-onset within the listening-trial was random. Target "on time" (duration) within the sea-noise was approximately 6 seconds. At the start of each trial, the subject first heard the target at 0 S/N, for a "familiarization" period. When the subject indicated he was ready, adaptive tracking testing began, and the target was presented, embedded in the noise, for a response at an appropriate S/N. If undetected, a more positive (easier) S/N was presented on the next trial; if detected, a more negative S/N was presented next from the matrix. As trials were presented, a change in performance from detection to failed detection, or its converse, was counted as a *reversal* in response.

The dB value half-way between successive *reversals* during a trial was recorded as threshold. From this, the absolute value of that threshold's deviation from the trial accumulated *mean* threshold was derived. The sum of these absolute values was used to determine the "average deviation" (AD), which had to be 2 dB or less. At the end of 6 thresholds, if the value of the *average deviation* exceeded 2, additional thresholds were measured until 6 successive thresholds yielded an AD of 2 dB or less. Once this criterion was met, the averaged threshold and AD were recorded for the completed trial.

RESULTS AND DISCUSSION

Data were subjected to a 2-way analysis of variance for repeated measures (Winer 1962). As seen in Table 1, results showed a significant difference in detection of targets with the experimental binaural display. As expected, individual targets are significantly different from one another in detection threshold. Also expected is the finding that differences in target detectability occur as a function of the display.

Table 1. **Results of 2-way repeated measures analysis of variance**

Source of Variation	SS	*df*	MS	F	p
Targets	2077.2	13	159.8	20.708	0.000000
Error	1604.9	208	7.7		
Beam-type	5560.5	1	5560.5	91.740	0.000000
Error	969.8	16	60.6		
Target x Beam-type	371.3	13	28.6	2.723	0.001413
Error	2181.5	208	10.5		

These results are best seen in Figure 5 which graphs the significant increase in detectability of *all* targets in the sample under the SVBF binaural presentation. Note that the averaged increase across targets was 6.8 dB. The figure graphs mean detection-

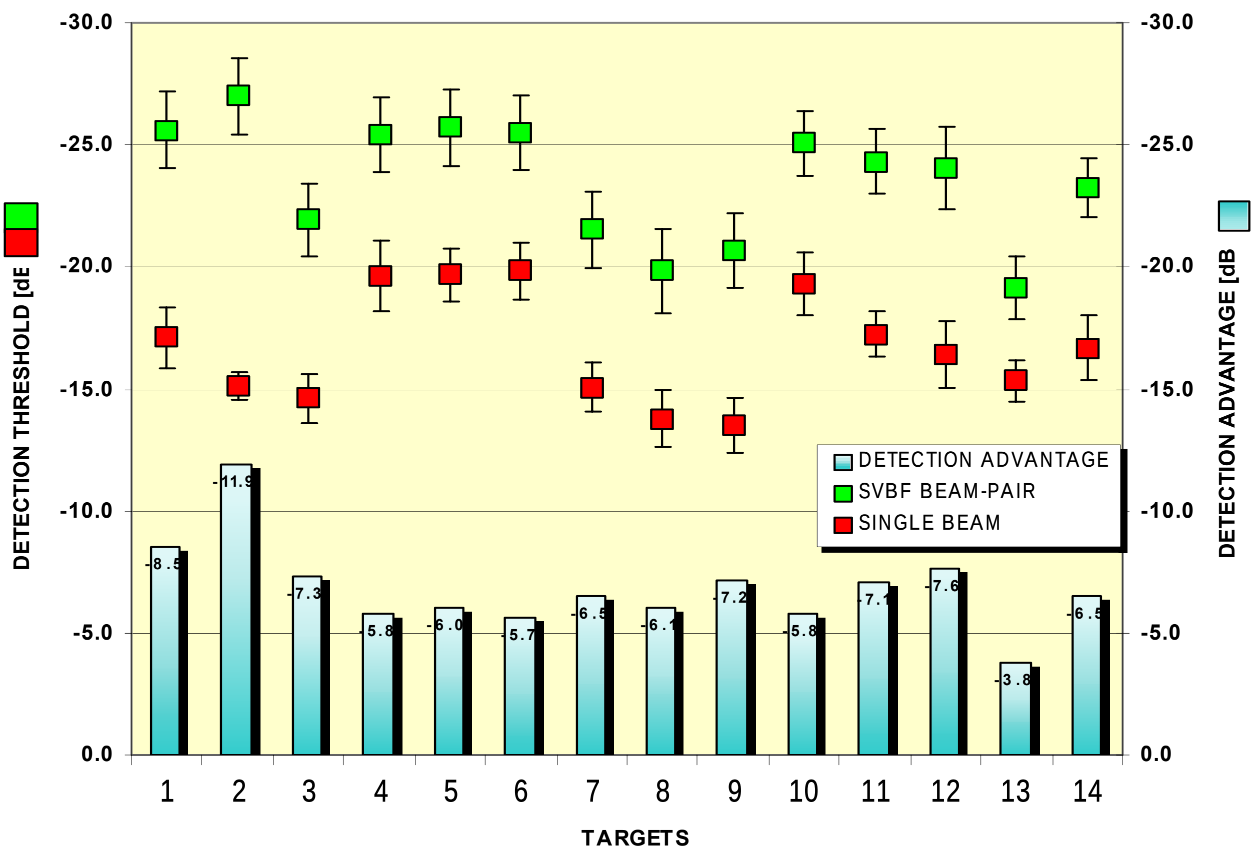

Figure 5. Detection advantage using a binaural SVBF presentation

threshold performance for each target, under both the conventional presentation and the spatial-vernier beam-pair. The error bars represent standard error of the mean. Detection advantage afforded by the SVBF display is also shown for each target. This detection advantage ranged from 12 to 4 dB. Note that, for each target, the variability in performance using the new SVBF *binaural* display was not much different from that found with the normal highly-familiar presentation. Again, given the fact that a 6 dB increase in is a doubling in distance from the target, these results are compelling. Unlike most novel situations, the variability in detection performance remained low with the new binaural display. Listening to the presentation, near threshold, quickly explains this outcome. The target is perceived to enter from "outside" the noise-field, and to one side. More striking is the ease in detecting the disappearance of the target. In the normal presentation detecting target onset is not as difficult as detecting when it fades. In the SVBF dual-beam presentation the disappearance of the target is quite salient as it ceases to emanate from "outside" the noise-field.

CONCLUSIONS

At the outset, we stated that the primary objective in this research was to apply the most sensitive capabilities of human auditory perception to passive sonar. It would be short sighted for sonar display developers to assume that the final outcome of these findings would simply be an auditory listening display. The unique aspect of this processing, is that it is a *real-time* display that *applies* human binaural signal processing to detect the presence of a spatially isolated signal in a complex field. Adaptive filtering can extract the localized real-time signal at a far more favorable S/N for further acoustic analysis or even code the unique target signature into a spatial presentation for contact management. Most relevant is the fact that, unlike time integrating signal analysis systems, the entire spectral envelope remains intact as a single sound source. Importantly, the real-time aspect is relevant for information, including temporally brief information, requiring immediate action.

The present research applied SVBF processes to the most basic current array, the line array. Follow-on from this research was a transition to apply this process to a more operationally useful, but far more complex, hydrophone array, the Wide Aperture Array or WAA. This research is currently underway using the same approach of signal analysis followed by signal processing of actual targets for assessment through human performance testing. From these performance results a beamforming methodology, perhaps independent from that successfully used for visual display presentation, will be recommended. This research would then become transitioned to 6.4 development. As an independent processor, now feasible within the modular design of Virginia class, hardware/software development could feasibly be accelerated for at-sea testing.

REFERENCES

Burbon, W.T., and Jeffress, L.A. (1965) Effect of bandwidth of masking noise on detection of homophasic and antiphasic tonal signals. J. Acoustic Soc. Am. 37, p. 1180A.

Deeb, S.S., (2000) Beam Noise Crosscorrelation for a Line Array, Naval Undersea Warfare Center, NPTRI Code 21, Technical Memo July 17.

Dolan, T.R., and Robinson, D.E (1967). Explanation of masking level differences that result from interaural intensive disparities of noise. J. Acoustic Soc. Am. 42 (5), pp. 977-981.

Durlach, N.I. (1972) Binaural signal detection: equalization and cancellation theory. In J.V. Tobias (Ed.) Foundations of modern auditory theory. New York: Academic Press. pp. 369-462.

Kerivan, J.E., (1980). Binaural detection of sonar signals. J. Acoustic Soc. Am. 68 (6), pp. 1696-1698.

Gersch, D.M., Russotti, J.S., and Kerivan, J.E., (1979). (U) Critical uses of analog audio display in passive sonar. Naval Submarine Medical Research Laboratory Report No. 903. CONFIDENTIAL.

Greenberg, J.E. and Zurek, P.M. (1992). Evaluation of an adaptive beamforming method for hearing aids. J. Acoustic Soc. Am. 91 (3), pp. 1662-1676.

Hanna, T.E., Russotti, J.S., and Marshall, L.M., (1988) (U) Auditory sonar: The importance of high quality channels in system design. Naval Submarine Medical Research Laboratory Report No. 1109. SECRET.

Harris, J.D. (1980) A comparison of computerized audiometry by ANSI, Bekesy fixed frequency, and modified ISC procedures in an industrial hearing conservation program. Naval Submarine Medical Research Laboratory Report, No. 930.

Heller, L., Russotti J.S., Carr, W., and Santoro T.P., (2000) Current NSMRL Information Processing and Display Research, Presented at Technical Workshop Poster session on Submarine Acoustic Superiority Proceedings Naval Undersea Warfare Center Report, May.

Hirsch, I.J. (1948) The influence of interaural phase on interaural summation and inhibition. J. Acoustic Soc. Am. 20 (4), pp. 536-544.

Jeffress, L.A. (1972) Binaural signal detection: vector theory. In J.V. Tobias (Ed.) Foundations of modern auditory theory. New York: Academic Press. pp. 349-368.

Langford, T.L. and Jeffress, L.A. (1964) Effect of noise crosscorrelation on binaural signal detection.. J. Acoustic Soc. Am. 36, pp. 1455-1458.

Licklider, J.C.R. (1948) The influence of interaural phase relations on upon the masking of speech by white noise. J. Acoustic Soc. Am. 20 (4), pp. 150-159.

Marshall, L.M., and Nash, M., (1990) (U) Analog Audio and Alarms on the AN/BQQ5 Sonar System: Sonar Technicians Ratings, Naval Submarine Medical Research Laboratory Report No. 1169. SECRET

Robinson, D.E. and Jeffress, L.A. (1963) effect of varying the interaural noise correlation on the detectability of tonal signals. J. Acoustic Soc. Am. 35 (12), pp. 1947-1952.

Russotti, J.S., (1987a) (U) Effects of system bandwidth on passive sonar target detection using normal and experimental auditory displays. Naval Submarine Medical Research Laboratory Report No. 1103. SECRET

Russotti, J.S., (1987b) (U) Experimental auditory display. Naval Submarine Medical Research Laboratory Report No. 1094. SECRET

Russotti, J.S., and Marshall, L.M., (1987). (U) Problems with current sonar system design. SECRET. Presented to Acoustic Analysis Working Group of the Atlantic Fleet Antisubmarine Warfare Improvement Program, Jacksonville, FL.

Russotti, J.S., and Wojtowicz, J., (1989) (U) Effects of degree of noise correlation on passive sonar target detection using experimental auditory displays, Naval Submarine Medical Research Laboratory Report No. 1139. SECRET

Russotti, J.S., Santoro, T.P., Hanna, T.E., Wojtowicz, J.J., (1993) Effects of digital sampling rate and bit quantization on passive auditory sonar target detection performance. Naval Submarine Medical Research Laboratory Report No. 1184.

Russotti, J.S., and Schwaller, D., (2001) Sensor-operator headset selection for Virginia Class Submarine Consoles [3CI]. Naval Submarine Medical Research Laboratory Report No. 1222.

Winer, B. J. (1962). Statistical Principles in Experimental Design. New York: McGraw-Hill.

Zurek, P.M. (1991) Probability distributions of interaural phase and level differences in binaural detection stimuli. J. Acoustic Soc. Am. 90 (4), pp. 1927-1932.

Statement of Significance: Technology developed here will provide crucial specifications for a tactical display that allows immediate interaural comparisons of angularly separated pairs of formed beams. This broader coverage binaural real-time display is ideal in littoral warfare. Performance gains such as simultaneous vs. serial comparison of beams of different azimuth or elevation, for rapid detection of acoustic changes (including transients), increased alerting cues from target apparent-motion "across the head" during sweep, and reduced operator uncertainty will significantly enhance crew safety in close-in operations.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
06-07-2005	Technical Report	March 2002 - September 2003

4. TITLE AND SUBTITLE
ADVANCED BINAURAL SONAR DISPLAY USING SPATIAL VERNIER BEAMFORMING

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Joseph S. Russotti
Mark A. Creese
Thomas P. Santoro

5d. PROJECT NUMBER
M04508.518

5e. TASK NUMBER

5f. WORK UNIT NUMBER
50211

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NAVSUBMEDRSCHLAB
Box 900
Groton, CT 06349-5900

8. PERFORMING ORGANIZATION REPORT NUMBER
NSMRL TECHNICAL REPORT #1240

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Operating in a dangerously sensor-limited closed environment, submarine sonar operators are plagued by primitive sensory interfaces inherited from earlier hardware designs. The inefficient match to the operator's perceptual capability is exacerbated as submarines increasingly operate in the littoral where, at now reduced ranges from quieter threat targets, detection requires immediate action for crew safety.

Present use of the sonar operator's auditory ability ignores the superior acuity of the mammalian binaural system. In humans, this system is sensitive to minute instantaneous differences in phase, intensity and time of arrival between its' two channels. This research developed, and perceptually tested, a binaural auditory display that optimized the essential noise correlation between a pair of formed listening beams. To generate the necessary perceptual characteristics for the binaural display, a breakthrough audio (cont.)

15. SUBJECT TERMS
Acoustics, Audio Engineering, Auditory discrimination, Beamforming, Binaural displays, Passive sonar, Psychoacoustics, Sonar Operator Performance, Digital processing, Psychometrics, Adaptive tracking, Perceptual testing, Auditory thresholds

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	SAR	18	M. Fitzgerald, Publications Manager	(860) 694-2442

beam-forming process formed beams from a simple linear hydrophone array which were *focused* at two different distances but in the same direction. This unique processing named Spatial Vernier Beamforming (SVBF) maintained the essential high noise correlation between the pair of formed directional beams. Once appropriate beamforming was proven feasible, laboratory testing was undertaken to quantify perceptual performance. A representative sample-group of 14 sonar contacts were beamform processed, and systematically presented to a group of 17 highly experienced sonar operators. Results show a highly significant 6.8 dB detection improvement over the current single beam display. This improvement represents the ability to acoustically detect targets at more than twice the distance currently achieved.

This signal processing technology provides an advanced auditory display which allows immediate interaural comparisons of pairs of focused beams. This broader coverage *binaural* real-time display is particularly well suited in littoral warfare. Performance gains such as: 1) simultaneous vs. serial comparison of beams of different distance, for more rapid detection of acoustic changes (including transients), 2) increased real-time information on target distance, 3) reduced operator uncertainty and increased alerting cues from target motion 'across the head' during sequential ranging, will significantly enhance crew safety in modern close-in operations. It can be linked to photonics mast display.

The SVBF dual beam data is ideal for adaptive *real-time* signal processing, since the noise common to the two beams can be mathematically removed to expose the target. As a result SVBF processes are amenable to real-time digital signal extraction for 3-D audio displays which are ideal for situational awareness.

Following positive findings using the simpler linear sonar array, SVBF processing is currently undergoing theoretical application to the Wide Aperture Array (WAA) which has far better bearing resolution. The broader bandwidth more perceptually useful WAA creates a greater challenge to applying this spatial-vernier beam-forming technique to a more complex beam-formed array.